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13. SUPPLEMENTARY NOTES

14. ABSTRACT

This program began May 15, 2007 and ended January 14, 2011. We have successfully accomplished not only the goals stated in the proposal but also beyond. There are three major achievements: (i) a sufficient condition for solar eruption, (ii) simulated Sun's emission and (iii) evolution of HCS during Cycle 23. Fourteen papers have been published or are in press at the Astrophysical Journal (ApJ), Journal of Geophysical Research (JGR) and in ASP Conference Series Proceedings and three have been submitted to Ap. J. and JGR journal and are under review. Overall, there are seventeen papers are a result of this grant. Please see the final report a summary of the highlights from this program.

15. SUBJECT TERMS

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FINAL REPORT & Attachment to SF298

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Contract/Grant Title: Development of a Data Driven Three-Dimensional Magnetohydrodynamic Model with Radiation Effects to Study Photopshere-Coronal Coupling
Contract/Grant #: FA9550-07-1-0468
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Principal Investigators: S. T. Wu, P.I. and: AiHua Wang, Co-I, Center for Space Plasma and Aeronomic Research, and Department of Mechanical & Aerospace Engineering, The University of Alabama in Huntsville, Tech Hall, Room N272B, 301 Sparkman Drive, Huntsville, AL 35899 USA (256) 824-6413
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Introduction

This program began May 15, 2007 and ended January 14, 2011. We have successfully accomplished not only the goals stated in the proposal but also beyond. Fourteen papers have been published or are in press at the Astrophysical Journal (ApJ), Journal of Geophysical Research (JGR) and in ASP Conference Series Proceedings and three have been submitted to Ap. J. and JGR journal and are under review. Overall, there are seventeen papers are a result of this grant. The highlights from this program are summarized in the following:

1. Fragmentation of the Length of Strong Magnetic Shear of the Main Neutral Line (L_{ss}): A Potential Sufficient Condition for Solar Eruption

A recent paper by Wu et al. (2009) has shown that the well-known non-potential magnetic field parameters (Falconer et al. 2002) are the necessary conditions but not sufficient for the initiation of solar eruptive events. In this study, we have used a three-dimensional data-driven MHD active region model (Wu et al. 2006) which is called Active Region Evolution Model (AREM) to analyze the magnetic field structures of an active region 10720. By inputs of the Big Bear Solar Observatory (BBSO) digital vector magnetograph (DGVM) to our AREM (Wu et al. 2006), we simulated the non-potential parameters (i.e. L_{ss}, length of strong magnetic shear of the main neutral line; magnetic flux (Φ); net electric current (I_N), and normalized measure of the field twist) at the time before and after a CME on January 15, 2005 as shown in Figure 1. The results indicate a general characteristic that all four non-potential magnetic parameters are increasing before the solar eruption, and decreasing after the solar eruption. Figure 2 shows the detailed evolution of the length of strong magnetic shear of the main neutral line (L_{ss}); we found from these results that the eruption does not occur at the left upper corner, even the length of L_{ss} is very long, but at the right upper corner when the length of the strong magnetic shear is fragmented, a CME was launched. This feature leads us to believe that the fragmentation may be an indicator for an eruption because it represents the inhomogeneity of magnetic shear along the neutral line. Since each segment has different twisting angle, this indicates a spaghetti type of magnetic field configuration. The MHD instability could easily be triggered, and lead to the eruption. Thus, this feature could be considered as a “sufficient” condition for the solar eruption. Most recently, we have requested Dr. David Falconer to examine some old data from NASA/MSFC’s vector magnetogram which also exhibits this same feature.

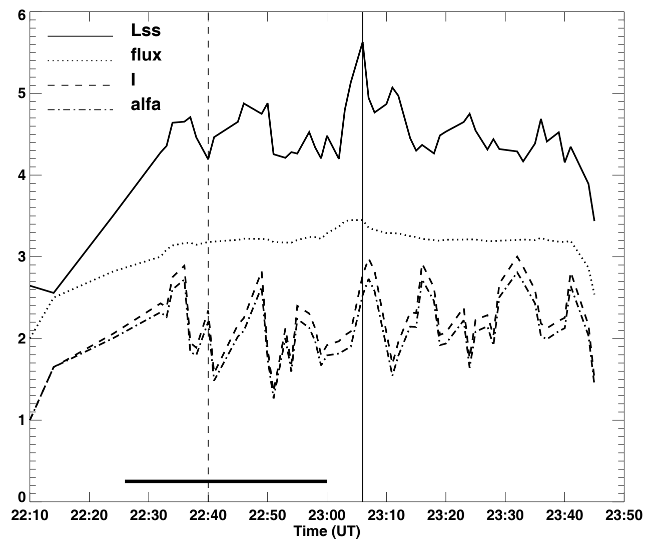

FIGURE 1. The simulated non-potential parameters (i.e. L_{ss}, length of strong magnetic shear of the main neutral line (unit 2×10^4 km); magnetic flux (Φ) (unit 5×10^{21} Mx); net electric current (I_N) (unit 3×10^{11} A); and normalized measure of the field twist (α) (unit 1.5×10^{-5} km)) at various times for AR10720, January 15, 2005. The horizontal bold line indicates the impulsive phase of a flare (onset-to-maximum of the soft X-ray emission), the vertical solid line shows the occurrence of a CME in the LASCO/C2 field of view, and the vertical dashed line indicates the back extrapolated time of the CME launch. (Wu et al. 2009)

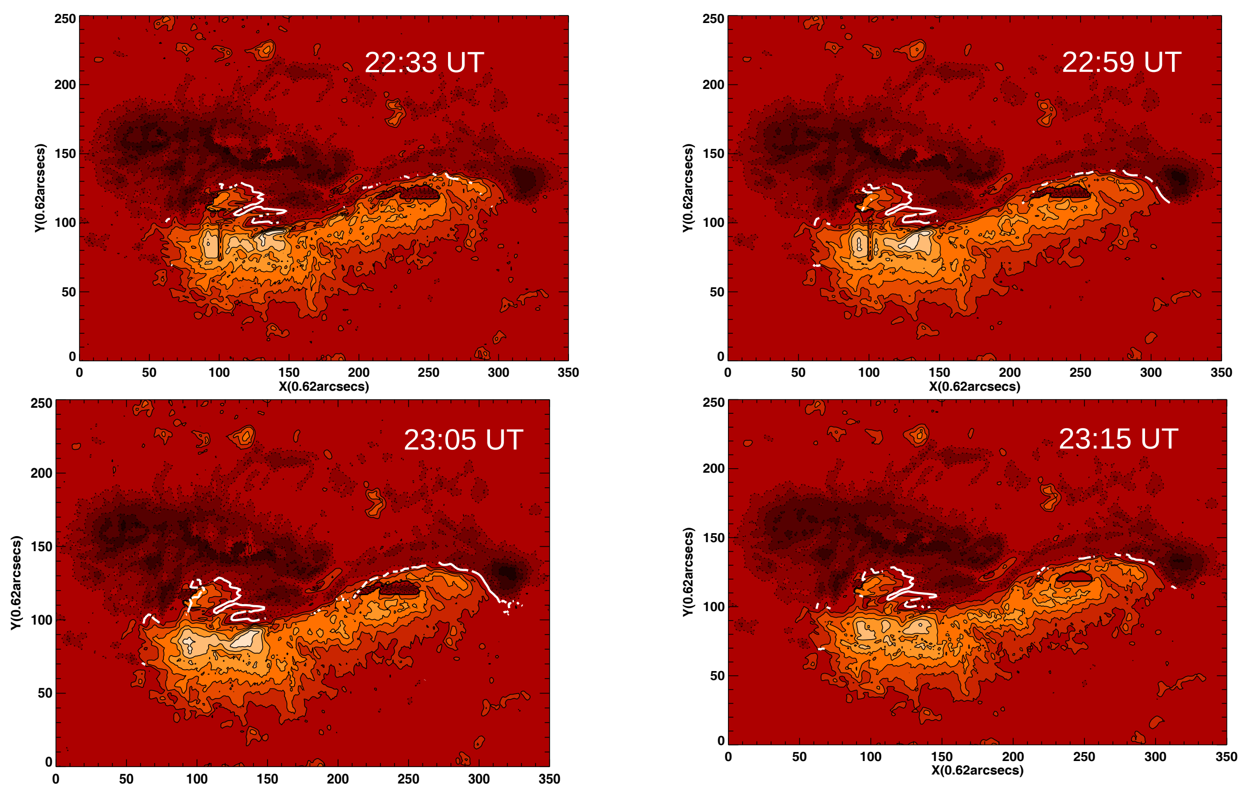

FIGURE 2. The simulated evolution of the length of strong magnetic shear of the main neutral line (L_{ss}) of AR10720 during the period 22:33UT to 23:15UT of January 15, 2005.

2. Simulation of the Sun's Emission

Our newly developed data-driven 3D MHD model with radiation effects was used to reproduce the Sun's emission. To carry out this simulation, we used the SOLIS measurements of line-of-sight (LOS) magnetic field and transverse velocity from GONG for CR2900 as inputs to the model in which the radiative emission and coronal magnetic field are obtained as shown in Figure 3(a,b). From this new robust simulation, we note that the closed field loop structures correspond to the high intensity of the emission and the open field region exhibits low emission with high speed solar wind. To verify the model, we have compared the simulated emission (i.e. synthetic image) of CR2900 (upper panel) and the observations of CR2900 EIT 304Å image (lower panel) in Figure 2. It shows good agreement.

Figure 3(a) shows the model output of the radiative emission on the photosphere and the 3D magnetic field topology is depicted in Figure 3(b). From these new robust simulations, we note that the closed field loop-structure produces high emission and the open field region exhibits low emission with high speed solar wind.

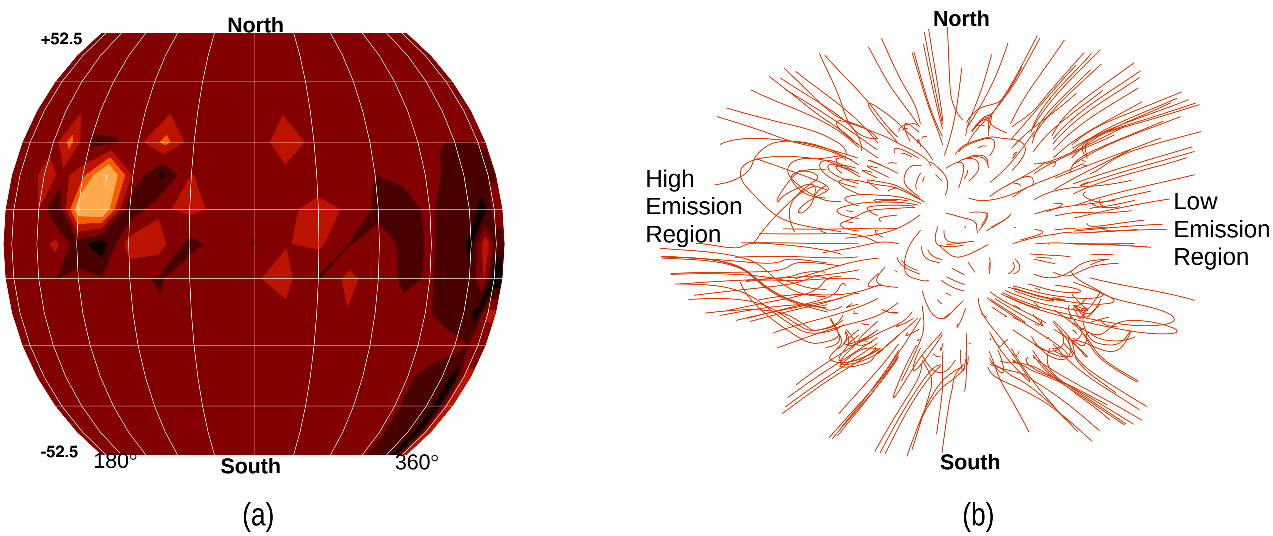

FIGURE 3. Simulated (a) sun's emission on the disk and (b) coronal magnetic field.

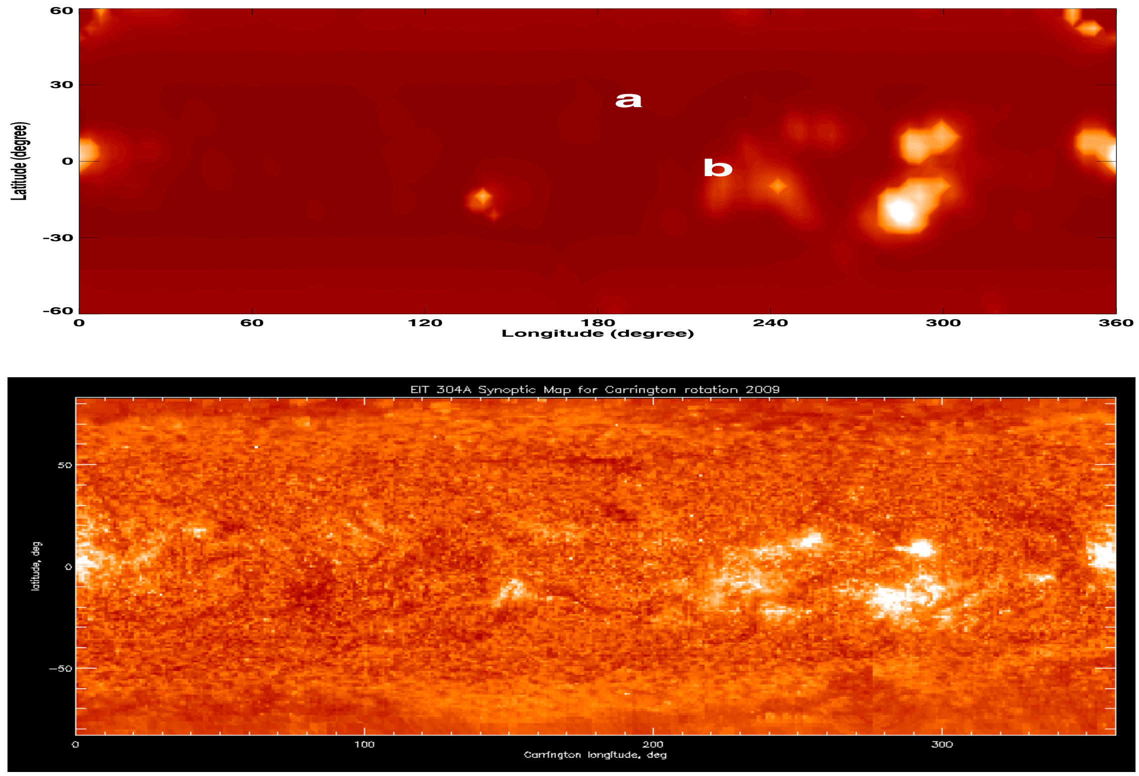

FIGURE 4. The synthetic image computed from the model density and temperature in unit DN/s/pixel: top panel with GONG's observed transverse velocity. The bottom panel is average EIT 304 image during CR2009 where "a" and "b" indicate the location of the inside and boundary of a coronal hole.

3. Evolution of the Heliospheric Current Sheet (HCS) and Coronal Magnetic Field Configuration for Solar Cycle 23.

The structure of the solar magnetic fields varies systematically over a period of about eleven years in relation to the four phases of the solar activity cycle. The four phases of the solar activity cycle are identified as: solar minimum, the rising phase, solar maximum and the declining phase. To investigate the solar cycle effects on HCS and coronal magnetic field, we have employed our 3D MHD model without radiation to simulate the evolution of HCS and coronal magnetic field configuration throughout Solar Cycle 23. This simulation is done by inputting observed line-of-sight photospheric magnetic field data from the Wilcox Solar Observatory (WSO) at the lower boundary. The simulation result is depicted in Figure 5. Note that the HCS at CR2050 (current minimum) is quite different from CR1910 (i.e. the solar minimum at the beginning of Solar Cycle 23). This observation shows the HCS at CR2050 exhibits a high inclination which is not flat as for CR 1910. The significance of this result is to provide the background solar wind to study the propagation of solar disturbance which has a major effect on the solar disturbance induced shock arrive time at Earth.

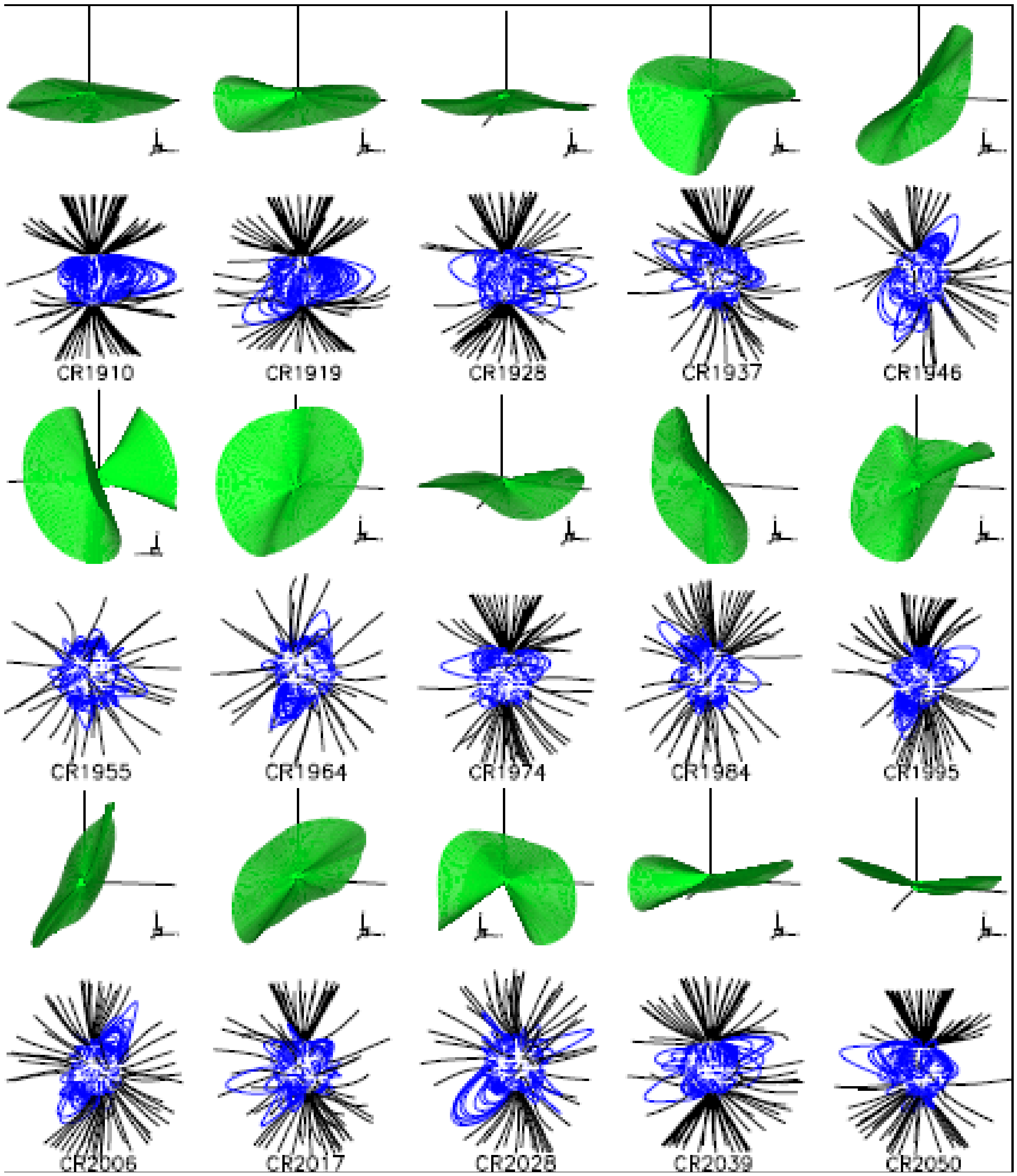

Figure 5. Evolution of the HCS topology and coronal magnetic field configuration throughout Solar Cycle 23. Five Carrington Rotations are classified into one group according to their associated phases in the solar cycle. The HCSs are shown above as the isosurfaces of $B_r = 0$ and the magnetic field configurations are shown below, respectively, for each Carrington Rotation; Field lines have been assigned as black for open field lines and blue for closed field lines; however, the same foot points at the photosphere are used in tracing the field lines for each Carrington Rotation (Hu et al. 2008).

PRESENTATIONS/TRAVELS

August 2007 – Meeting with Prof. Frank Hill (National Solar Observatory) regarding GONG data

January 2008 – Attend and participate at the AIAA Aerospace Sciences Meeting at Reno, Nevada

March 2008 – Presented Construction of 3D Active Region Fields and Plasma Properties using Measurements (Magnetic Fields & Others) and Participate in scientific discussion with solar group at Stanford University and attend and participate at the SDO-HMI/EVE/AIA Science Team Meeting at Napa, California

June 2008 – Attend and participate at the 39th AIAA Plasmadynamics and Lasers Conference, Seattle, Washington

July 2008 – Presented Analyses of Magnetic Field Structures for AR 10720 using a data-driven 3D MHD Model at Committee on Space Research Meeting, Montreal, Canada

August 2008 – Visit Dr. B. Tsurutani at JPL regarding collaborative research on 3D MHD model with radiation effects and Dr. Liu at Stanford University regarding analysis using DD3D MHD model

April 2009 – Presented Summary of the data driven compression resistive 3D MHD model and visit Stanford University to participate in a meeting regarding data analysis tool for the data center in response to the upcoming SDO/HMI launch, San Francisco, CA

May 2009 – Visit U de Barcelona for space weather model research discussions with Dr. Blai Sanahuji, Prof. of Astrophysics, Barcelona, Spain

June/July 2009 – Presented Characteristic Boundary Conditions for Numerical (MHD) Simulation of Solar and Laboratory Plasma Dynamics at ASTRONUM-2009, Chamonix, France

June/July 2009 - A Three-Dimensional Solar Wind Model Based on Surface Measurements of the Magnetic Field and Velocity Field from GONG S T. Wu, A. H. Wang, F. Hill and I. Gonzalez, 12th International Solar Wind Conference at St. Malo, France

July 2009 – Presented Modeling of Sun-Earth Connection with Sub-Photosphere Effects, Atmospheric Neutral Density Research Review Workshop, Colorado Springs, CO

August 2009 – Attend and participate at the 2009 SHINE meeting, Wolfville, Nova Scotia

September 2009 – Presented Three-Dimensional MHD Modeling of Sun-Earth Connection with Sub-Photosphere Effects, Naval Research Laboratory, Washington, DC

Oct/Nov 2009 – Presented the Progress of MHD Simulation of Solar Atmospheric Dynamics and visit Dr. B. Tsurutani at JPL regarding collaborative research on 3DMHD model with radiation effects Los Angeles, CA and Visit Dr. Liu at Stanford University regarding analysis using data driven 3D MHD model, San Francisco, CA

December 2009, Non-force-free Extrapolation of Coronal Magnetic Field with Applications to Vector Magnetograms, Q. Hu, A. H. Wang, B. Dasgupta, G. A. Gary, and S. T. Wu, and MHD Shocks Driven by Jets/CMEs without Flux-Rope Topology and Origin of 3He-Rich SEP Events, by T. X. Zhang, S. T. Wu, A. Tan, A. T. Broaden, and M. Jadhav, both presented at the 2009 Fall American Geophysical Union Meeting, San Francisco, CA

January 2010 - The Role of Magnetic Reconnection in CME Acceleration, S T. Wu, National Space Science & Technology Center/UAH/CSPAR Colloquium, Huntsville, AL

February 2010 - Visit Drs. Chin-Chun Wu and Simon Plunkett at the Naval Research's Space Science Laboratory to discuss collaborative research on solar terrestrial physics research and participate as a NSF-DOE Review Panel Member, Washington, DC

March 2010 – Acceleration and Deceleration of Coronal Mass Ejections, S. T. Wu, A. H. Wang, C. C. Wu and K. Liou, STEREO Science Working Group meeting and 9th SECCHI Consortium Meeting, Dublin, Ireland

April 2010 - Visit with Drs. Liu & Zhao at WW Hansen Experimental Physics Laboratory, Stanford University to discuss data for the analysis using data driven 3D MHD model, Stanford, CA

May 2010 - A Combined Approach for Coronal Magnetic Field Modeling, Q. Hu, A. H. Wang, S. T. Wu, G. A. Gary, AAS/Solar Physics Division Meeting, Miami, FL

June 2010 - SDO data collaboration with Drs. Liu & Zhao at WW Hansen Laboratory, Stanford University, Stanford, CA

June 2010 – Presented A global solar wind model based on photospheric surface measurements of magnetic field and transverse velocity from GONG, ASTRONUM – 2010, 5th International Conference on Numerical Model of Space Plasma Flows, San Diego, CA

June 2010 - Attend and participate at the 41st AIAA PD&L Conference Chicago, IL

June 2010 – Presented Conditioning of Solar Wind Based on Multiple Measurements on the Sun's Surface, Presented A 3D Solar Wind Model and Solar Surface Properties Based on Surface Measurements of the Magnetic Field and Velocity Field from GONG, both at Western Pacific American Geophysical Union Meeting, Taipei, Taiwan

July 2010 - To attend and participate in SCOSTEP 2010 to present MHD Simulation of the Correspondence of an EIT Wave, CME, and ICME and meet with international colleagues prior to and after the main SCOSTEP Conference at Berlin, Germany and visit the Observatoire de Paris (Dr. Brigitte Schmeider) for discussion of collaborative research on space weather, active regions and solar prominences, Paris, France

July 2010 - Acceleration of Solar Energetic particles by CME Induced Shocks, C. C. Wu, D. Berdichevsky, K. Liou, S. T. Wu, M. Dryer and A. Tylka, to be presented at the 38th COSPAR Scientific Assembly 2010, Germany

August 2010 - visit Dr. Liu at Stanford University regarding analysis using SDO observation data for DD 3D MHD model

September 2010 – Presented Quantification of Solar Eruptive parameters and spectral irradiance prediction using a data driven 3D MHD Model and presented A New Solar Mission for Cycle 24: Solar Dynamics Observatory, China/Taiwan

December 2010 – On the Causes of Plasmoid Acceleration and Change of Magnetic Reconnection Rate in a Resistive MHD Simulation; Three-Dimensional Global Simulation of Coronal Mass Ejections with Flux Rope Structures; The First Reseults of Solar Wind Background Study by 3D SIP-AMR-CESE MHD Model; Optimal Pre-Initial Conditions for Data Driven MHD Simulation of Solar Active Regions; Comparative Analyses of Productive and Non-Productive Active Regions based on SDO/HMI Observations using a 3D Data Driven Active Region Evolution Model (DDAAREM); MHD Shocks Driven by Jets/CMEs without Flux Rope Topology and Origin of 3He-Rich SEP Events; Heliospheric 3D Global Simulation of CMEs; all presented at the 2010 Fall American Geophysical Union Meeting, San Francisco, CA

Publications:

1. Wang, A. H., S. T. Wu, E. Tandberg-Hanssen and Frank Hill, Utilization of Multiple Measurements for Global 3D MHD Simulations, *Ap.J.*, 2011 (in press, 2011)

2. Wu, S. T., A. H. Wang, C.-C. Wu, F. Hill, I. Gonzalez Hernandez, X. S. Feng, and M. Dryer, A Global Wind Model Based on Surface Measurements of Magnetic Field and Transverse

Velocity from GONG, Proceedings of the ASTRONUM – 2010, 5th International Conference on Numerical Model of Space Plasma Flows, San Diego, CA, ASP Conference Series, (submitted Jan 2011)

3. Hu, Q., A. H. Wang, S. T. Wu, and G. A. Gary, A combined Approach for Coronal Magnetic Field Modeling, Ap. J., (submitted July 2010)

4. Shen, F., X. S. Feng, S. T. Wu, C. Q. Xaing, and W. B. Song, Three-Dimensional Numerical MHD Simulation of the Evolution of the April 2000 CME Event and Its Induced Shocks using a Magnetized Plasma Blob Model, JGR (submitted June 2010)

5. Liu, Y., P. H. Scherrer, J. T. Hoeksema, J. Schou, T. Bai, J. G. Beck, M. Bobra, R. S. Bogart, R. I. Bush, S. Couvidat, K. Hayashi, A. G. Kosovichev, T. P. Larson, C. Rabello-Soares, X. Sun, R. Wachter, J. Zhao, X. P. Zhao, T. L. Duvall, Jr., M. L. DeRosa, C. J. Scjhrijver, A. M. Title, R. Centeno, S. Tomczyk, J. M. Borrero, A. A. Norton, G. Barnes, A. D. Crouch, K. D. Leka, W. P. Abbett, G. H. fisher, B. T. Welsch, K. Muglach, P. W. Schnuck, T. Wiegelmann, M. Turmon, J. A. Linker, Z. Mikic, P. Riley, S. T. Wu, A First Look at Magnetic Field Data Products from HMI/SDO, ASP Conference Series, Astronomical Society of the Pacific, 2011 (in press)

6. Wu, S. T., A. H. Wang and J. Cassibry, Characteristic Boundary Conditions for Numerical Magnetohydrodynamic (MHD) Simulation of Solar and Laboratory Plasma Flows, in Proceedings of ASTRONUM 2009, Numerical Modeling of Space Plasma Flows, Astronomical Society of the Pacific Conference Series, Volume 429, (eds. N. V. Pogorelov, E. Audit, G. P. Zank), 294-304, 2010

7. Yu, H. S., L. H. Lyu and S. T. Wu, On the Causes of Plasma Acceleration and Changes of Magnetic Flux in a Resistive MHD Plasma, Astrophysical Journal, 727:79(12pp), doi:10.1088/0004-637X/726/79, 2011

8. Feng, X. S., L. Yang, C. Q. Xiang, S. T. Wu, Y. F. Zhou, and D. K. Zhong, Three-Dimensional Solar Wind Modeling from the Sun to Earth by SIP-CESE MHD Model with Six-Component Grid, The Astrophysical Journal, 723, 300-319, doi:10.1088/0004-637X/723/1/300 2010

9. Zhao, H., X. S. Feng, C. Q. Xiang, Y. Liu, Y. Zhang, and S. T. Wu, Multi-Spacecraft Observations of the 2008 January 2 CME in the Inner Heliosphere, X. Astrophysical Journal, 714, 1133-1141, doi 10.1088/0004-637X/7142/1133, 2010

10. Feng, X. S., Y. Zhang, L. P. Yang, S. T. Wu and M. Dryer, An Operational Method for Shock Arrival Time Prediction by 1D CESE-HD Solar Wind Model, J. Geophys. Res., 114, A10103, doi 10.1029/2009JA014385, 2009

11. Zhang, T. X. and S.T. Wu, Magnetohydrodynamic Simulation of Non-flux Rope Coronal Mass Ejection, J. Geophys. Res., 114, A05107, doi:10.1029/2008JA013860, 2009

12. Wu, S. T., A. H. Wang, G. Allen Gary, Ales Kucera, Jan Rybak, Yang Liu, Bojan Vrsnak, Vasyl Yuchyshyn, Analyses of Magnetic Field Structures for Active Region 10720 using a Data-Driven 3D MHD Model, Adv. Space Res., 44, 46-53, doi:10.1016/j.asr.2009.03.020, 2009

13. Wu, S. T., Ai-Hua Wang, C. D. Fry, XueShang Feng, Chin-Chun Wu, and Murray Dryer,Challenges of Modeling Solar Disturbances' Arrival Time at the Earth, Science in China Series E, Technological Sciences, 51(10), 1580-1588, Oct. 2008

14. Wang, A. H., S. T. Wu, Y. Liu, and D. Hathaway, Recovering Photospheric Velocities from Vector Magnetograms by using a Three-Dimensional, Fully Magnetohydrodynamic Model, Astrophysical Journal Letters, 674:L57-L60, 2008

15. Hu, Y. Q., X.S. Feng, S. T. Wu and W. B. Song, Three-Dimensional MHD modeling of the Global Corona throughout Solar Cycle 23, Y. Journal of Geophysical Research, Vol. 113, A03106, doi:10.1029/2007/JA012750, 2008

16. Zhou,Y-F, X-S Feng, and S. T. Wu, Numerical Simulation of the 12 May 1997 CME Event, Chinese Physics Letters, 25(2), 790, 2008

17. Gary, G.A., S. T. Wu and A. H. Wang, Analyses of Hinode Magnetic Field Observations Using a 3D MHD Model, Proceedings of The First Results from Hinode, Dublin, Ireland, August 20-24, 2007, Sarah Matthews, John Davis and Kazunari Shibata, Eds. Astronomical Society of the Pacific (ASP) Conference Series (2008)

Changes in research objections, if any: NONE

Changes in AFOSR program manager, if any: YES, the current program manager is Dr. Cassandra Fesen, Program Manager, Space Science, Physics and Electronics Directorate, AFOSR/RSE875 N. Randolph Street, Arlington, VA 22203, (703) 588-8315, cassendra.fesen@afosr.af.mil

Extensions granted or milestones slipped, if any: Yes, Grant/Cooperative Agreement Amendment #P00004 effective June 15, 2010 was issued to change the duration of the grant from 37.5 to 44.5 months and extend the period of performance through 14 January 2011.

Include any new discoveries, inventions or patent disclosures during this reporting period (if non, report none): We discovered a sufficient condition for the solar eruption by analyzing AR 10720 magnetic structure as discussed in this technical report.